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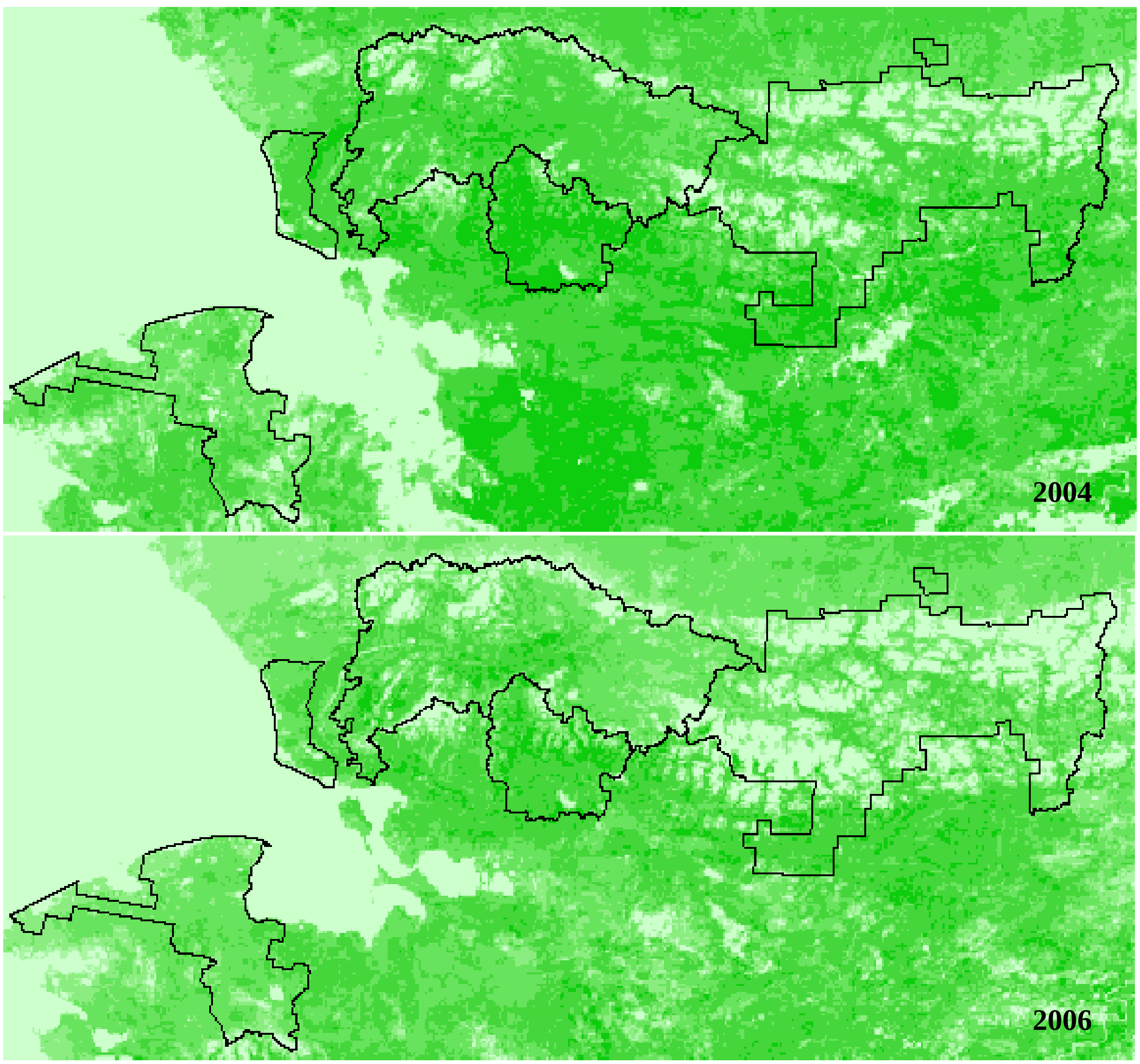
Satellite Greenness Data Summary for the Arctic Inventory and Monitoring Network, 1990-2009

Natural Resource Data Series NPS/ARCN/NRDS—2010/124



ON THE COVER

Normalized difference vegetation index (NDVI) images of northwestern Alaska, for early July in 2004 (upper) and 2006 (lower). High NDVI values are display as darker green. June of 2004 was warmer than average and June of 2006 was cooler than average, resulting in higher NDVI values in 2004. ARCN NPS units are outlined. Computed from MODIS satellite imagery

Satellite Greenness Data Summary for the Arctic Inventory and Monitoring Network, 1990-2009

Natural Resource Data Series NPS/ARCN/NRDS—2010/124

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U.S. Department of the Interior
National Park Service
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Abstract

Normalized difference vegetation index (NDVI) derived from AVHRR and MODIS satellite sensors is summarized in five northern Alaskan National Park Service units dominated by arctic tundra. NDVI is an index of vegetation productivity that is closely related to the warmth of summer growing seasons in the arctic. Mean NDVI for ecological sections (broad landscape-scale mapping units) is highest for densely vegetated lowlands, lowest in sparsely vegetated high mountain areas, and intermediate in lowlands with significant area of lakes. NDVI during green-up (June) varies 20 to 40% between years, while peak NDVI and late-season NDVI vary 10 to 20% between years. These short-term variations are closely linked to current-year variations in growing-season temperatures. Over the past 20 years (1990-2009), summer NDVI has increased 10% to 20% in the more heavily vegetated ecological sections. These long-term increases in NDVI suggest an increase in vegetation biomass, possibly due to shrub expansion.

Introduction

Monitoring of vegetation phenology (green-up and senescence) by satellite imagery has been identified as an important component of the monitoring program for the Terrestrial Landscape Patterns and Dynamics vital sign of the National Park Service (NPS) Arctic Inventory and Monitoring Network (ARCN) (Lawler et al., 2009). Our goal is to track both year-to-year variability and long-term changes in vegetation productivity during different parts of the growing season. This information will help us understand variations in wildlife forage availability and habitat quality (e.g. Griffith et al., 2002), as well as trends in vegetation structure and ecosystem productivity.

Satellite measurements of the normalized difference vegetation index (NDVI) are a widely accepted measure of vegetation greenness and a proxy for productivity or biomass (Tucker and Sellers 1986). NDVI is computed from the near infrared (NIR) and red (R) spectral reflectance of remotely sensed imagery: NDVI = (NIR – R)/(NIR + R). Green vegetation reflects strongly in the NIR band and absorbs strongly in the R band. Thus densely vegetated areas have NDVI approaching 1, while unvegetated areas have NDVI near or below zero.

Multi-day compositing of NDVI values helps to circumvent problems caused by clouds obscuring the ground (Holben, 1986). The maximum NDVI value is selected for each pixel from a range of days (typically one or two weeks), and these maxima are displayed in a composite image that mimics a single cloud-free scene. These NDVI composite images can then be compared to track changes in vegetation greenness through the seasons or between years. Two public sources of NDVI composites were analyzed in the present study, one computed from weather satellite data (AVHRR) and another with satellite data of finer resolution but shorter period of record (MODIS)(Table 1). A third source of NDVI data, the Global Inventory Modeling and Mapping Studies GIMMS data set from the NASA Goddard Space Center (Pinzon and Brown, 2004), was considered but not used because of its coarser resolution (8 km pixels), lack of cloud screening, and the fact that it is based on the same satellite readings as the AVHRR data.

Comparison of NDVI values from AVHRR and MODIS sources have shown them to be very similar, though NDVI values calculated from MODIS data are typically slightly higher due to differences in the exact definitions of the wave bands (Gallo et al., 2005). The MODIS data offer a higher spatial resolution than AVHRR but a shorter period of record (Table 1).

Vegetation biomass in the arctic consists almost entirely of slow growing, long-lived perennial species whose growth is limited by cold (Billings and Mooney, 1968). Most of the annual rise and fall in NDVI, and the between-year variations in NDVI for a particular season, are the result of different amounts of leaf area produced by deciduous perennials in response to variations in temperature (Huemmrich, 2010). The immediate effect of cold weather during May, June and July in the arctic and subarctic is to delay or reduce the formation of leafy biomass, thus reducing NDVI. Warm summers allow greater vegetation productivity, with important implications for wildlife (Griffith et al., 2002). In contrast to short-term changes, long-term changes in NDVI (i.e., over a period of 10 or more years) suggest a change in perennial vegetation biomass and structure. Shrub tundra has a higher NDVI than herb-dominated tundra (Jia et al., 2004), and increasing greenness of arctic Alaska over the period 1982-2003 has been attributed to increasing shrub cover (Verbyla, 2008).

The purpose of this report is to summarize the available time-series of NDVI data for ARCN, to quantify year-to-year variability in NDVI and verify its known relationship with air temperature, to look at long-term trends in NDVI, and examine regional differences in NDVI within ARCN.

Table 1. Sources of satellite NDVI data

Greenness of the Conterminous US and Alaska
NDVI calculated from AVHRR (Advanced Very High Resolution Radiometer, weather satellites) data at 1 km resolution for the United States by USGS-EROS. Maximum NDVI with 7 and 14-day compositing periods. Images consist of 14 bands, including NDVI, a cloud mask, date index, the raw reflectance values, and satellite characteristics. Available 1989 to 2009. Images may be downloaded as band-sequential binary rasters from USGS or accessed from a Web Coverage Service (WCS) by the University of Alaska Geographic Information Network for Alaska (GINA). More information:
http://eros.usgs.gov/ecms/documents/products/AVHRR_Readme.doc (data description)
http://ivm.cr.usgs.gov/ (Greenness of the U.S. program website).
http://earthexplorer.usgs.gov (for ftp download from USGS)
http://www.gina.alaska.edu (University of Alaska GINA WCS)

MODIS Land
Global NDVI from MODIS (Moderate Resolution Imaging Spectroradiometer) satellite data. NDVI in Alaska is from the MODIS Terra satellite and is available at 250 m, 500 m, or 1 km resolution with 7-day compositing. Includes a data quality image that identifies pixels covered by clouds or snow on the composite. Available 2000 to 2009. Images may be downloaded as zipped GeoTIFF images from the USGS or accessed from a Web Coverage Service (WCS) by the University of Alaska Geographic Information Network for Alaska (GINA),
More information:
Jenkerson et al. (2010)
http://modis-land.gsfc.nasa.gov/ (MODIS Land program website)
http://landportal.gsfc.nasa.gov/Documents/eMODIS_readme_Alaska_121108.doc (data description)
ftp://emodisftp.cr.usgs.gov/eMODIS/Alaska/ (ftp download from USGS)
www.gina.alaska.edu (University of Alaska GINA WCS)

Study Area

The study area is the National Park Service units of the Arctic Inventory and Monitoring Network (ARCN) (Fig. 1). Vegetation in this region is dominantly tundra. Spruce (*Picea*) and birch (*Betula*) forests occur at low elevations in southern KOVA and GAAR (see Fig. 1 for park unit abbreviations) and cover about 9% of ARCN (Jorgenson et al., 2010). Lowland tundra is dominated by graminoids (*Eriophorum* and *Carex*) and shrubs (*Betula*, *Salix*, *Alnus*, and shrubs from the family Ericaceae). High elevations are sparsely vegetated.

Long-term climate records (1971-2000) from Bettles (in low-elevation forest south of GAAR, Fig. 2) show mean temperatures of -24.0 °C in January and +15.7 °C in July, and at Kotzebue (in tundra on the west coast, Fig. 2), -19.1 °C in January and +12.6 °C in July (Western Regional Climate Center, 2010). Snow cover at both localities usually becomes established in October and disappears in May. Summer temperatures are highest in southerly, inland, low-elevation areas similar to Bettles, and summers are cooler at higher elevations and at more northerly and westerly (coastal) locations. Mean July temperatures approach 0 °C in some high-elevation parts of GAAR (PRISM Climate Group, 2009).

NDVI data were summarized by ecological sections ("eco-sections"), which represent extensive areas with a uniform physiography and regional climate (Cleland et al., 1997; Fig. 2). Because there are many (31) eco-sections in ARCN, some of which are located mainly outside of the NPS unit boundaries, I chose 8 representative sections for this summary (Fig. 2; Table 2.). Sections were chosen to represent a wide range in environmental conditions; one section was chosen in each of the small NPS units (CAKR and KOVA) and two sections in each of the three larger NPS units.

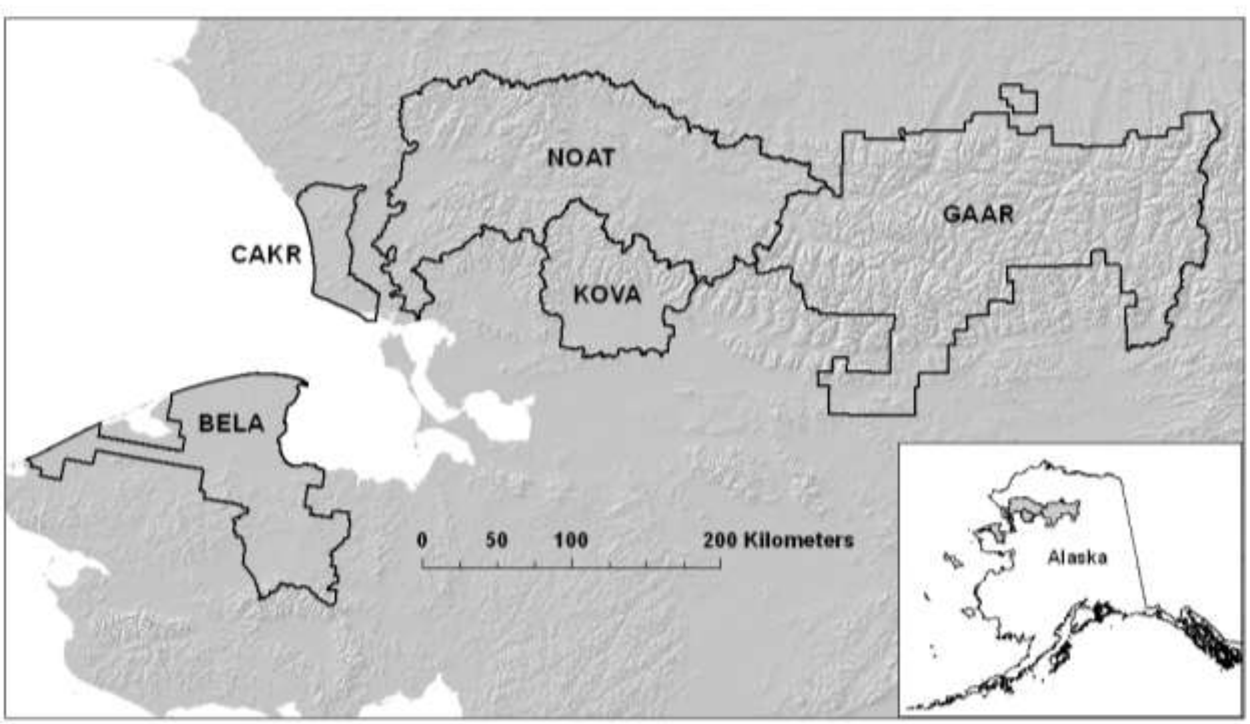

Fig. 1. The Arctic Inventory and Monitoring Network (ARCN) includes five Alaskan National Park Service units: Bering Land Bridge National Preserve (BELA), Cape Krusenstern National Monument (CAKR), Kobuk Valley National Park (KOVA), Noatak National Preserve (NOAT), and Gates of the Arctic National Park and Preserve (GAAR)).

Table 2. Ecological sections analyzed in this report

Section	Description
Arctic Brooks Range	Rugged mountains, continental (eastern) location, mostly north of the crest of Brooks Range, tundra or sparse vegetation.
Bering Sea Coastal Plain	Tundra lowland with maritime climate and many lakes.
Chukchi Sea Coastal Plain	Tundra lowland with maritime climate.
Delong Mountains	Rugged mountains, western limit of the Brooks Range, tundra or sparse vegetation.
Imuruk Plain	Tundra lowland with transitional maritime-continental setting
Kobuk River Lowland	Lowland with boreal forest vegetation.
Noatak Basin	Tundra lowland with continental location.
Subarctic Brooks Range	Rugged mountains, continental (eastern) location, mostly south of the crest of Brooks Range, mostly tundra or sparse vegetation with small forested areas.

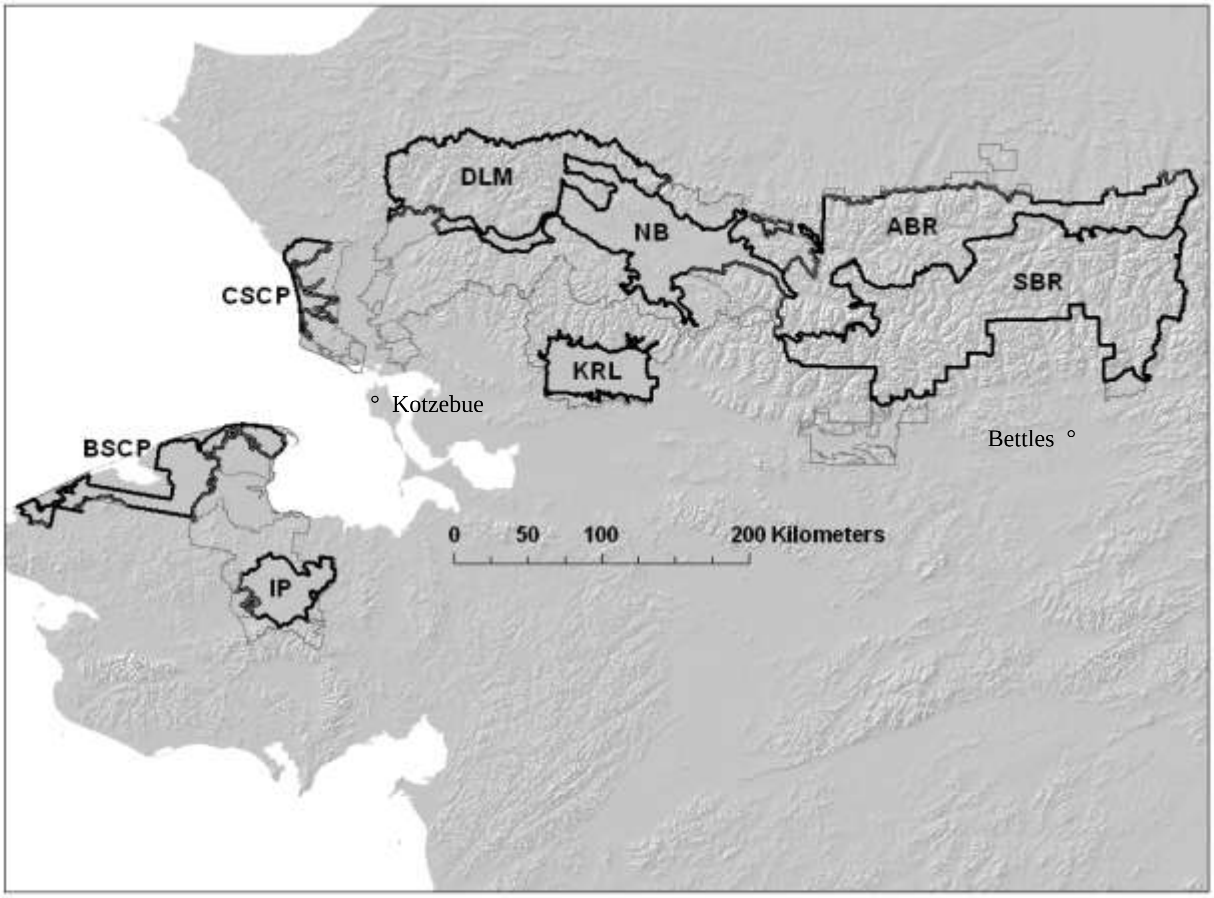

Fig. 2. ARCN Ecological Sections. Fine lines outline all ecological sections in ARCN. Bold lines outline sections chosen for NDVI data summary. ABR–Arctic Brooks Range, BSCP–Bering Sea Coastal Plain, CSCP–Chukchi Sea Coastal Plain, DLM–Delong Mountains, IP–Imuruk Plain, KRL–Kobuk River Lowland, NB–Noatak Basin, SBR–Subarctic Brooks Range. Section mapping by Boggs and Michaelson (2001), Jorgenson (2001), Jorgenson et al. (2001), and Swanson (2001a, b).

Methods

AVHRR

Though both 1-week and 2-week AVHRR NDVI composites are available, the 2-week composites were chosen for analysis here because 1) for several years (1992-1994) only 2-week composites are available, 2) longer compositing periods reduce cloud contamination problems, and 3) longer compositing periods are less sensitive to the between-year inconsistencies in start and end dates of the compositing periods in the AVHRR data set. To assemble a full 20-year time series requires use of compositing periods that vary in start and end date by 6 days between years. In the case of 2-week composites this still results in considerable overlap between years.

Composite images were downloaded from http://ndvi.gina.alaska.edu/XXXX/avhrr?, where XXXX is the year. Each year of data, clipped to the ARCN NPS unit boundaries, took about half an hour to download and occupied about 100 MB of disk space. The cloud mask image band was used to recode cloudy pixels as “no data” before running the ArcGIS “Zonal Statistics as Table” geoprocessing routine (ESRI, 2010). Mean NDVI and proportion of cloudy pixels were computed from each composite image for the 8 representative ecological sections (Fig. 2). The results of this summary were included in further analysis (regression against year or climate variables) only if at least 80% of the pixels in the section were labeled as cloud free. About 80% of the composites from the June-August period met this quality criterion. Composites with a high proportion of cloudy pixels were considered potentially biased because they are missing large parts of the section, plus I noted that they frequently have unexpectedly low NDVI values, suggesting cloud contamination even in the pixels labeled as "good".

As mentioned above, to assemble a long time series of AVHRR composites one must accept some variation in start and end dates of compositing periods. For this analysis I used 2-week composites with start day of the year of 151-156 for early June, 166-172 for late June, 181-187 for early July, 197-203 for late July, 212-218 for early August, and 228-234 for late August.

To examine the long-term trends in NDVI for the various ecological sections, mean NDVI in each compositing period was regressed against the year. To investigate the relationship between NDVI and air temperature at Bettles and Kotzebue, the late June average NDVI values for sections were regressed against mean May-June and June temperature for each year.

MODIS

The highest spatial resolution data (250 m) were chosen for analysis. The weekly NDVI composites plus the quality images were downloaded from http://ndvi.gina.alaska.edu/XXXX/modis?, where XXXX is the year. Each year of data, clipped to the ARCN NPS unit boundaries, required about 4 hours to download and occupied approximately 1 GB of local disk space. The quality image was used to recode cloud, snow, or bad-data pixels as "no data" before running zonal statistics for ecological sections. Data are summarized here for the 8 representative ecological sections (Fig. 2). Data from an ecological section were included in the analysis only if more than 80% of the pixels were labeled as "good" (free of clouds, snow, or errors), because, as discussed above for the AVHRR data, cloud contamination problems appear to affect pixels labeled as "good" in composites with more than 20% clouds (Fig. 3). As in the case of the AVHRR data, about 80% of the June-August images met the quality threshold.

The NDVI data from several consecutive compositing periods were aggregated into seasons, yielding a greenness rating for every season in every section and year, in spite of missing data due to compositing periods rejected because of clouds. The seasons that are of particular interest and are summarized here include: green-up (days 155-182, June), peak greenness (days 197-224, late July-early August), and senescence (days 225-252, mid-August to early September). The MODIS data has consistent start and end dates of compositing periods between years, which makes between-year comparisons easier than in the case of AVHRR composites.

I chose not to simply average the available MODIS NDVI values from the various compositing periods within a season, because NDVI changes rapidly in the green-up and senescence periods, and thus omission of a value due to clouds could severely bias the mean. For example, a missing value from late in the green-up, when NDVI is highest, would depress the computed mean NDVI for the green-up season as a whole. To avoid this problem, I normalized the NDVI value of each eco-section in each year and compositing period by computing Z-scores (standard normal deviates) for the NDVI value, using the mean and standard deviation of that compositing period and eco-section for all years. The Z-scores of available compositing periods within a season were then averaged to arrive at a score for the season. These normalized average scores were then ranked (i.e. to determine which years were the greenest) and also regressed against year to determine if years with high greenness ranks became more common later in the 2000-2009 decade.

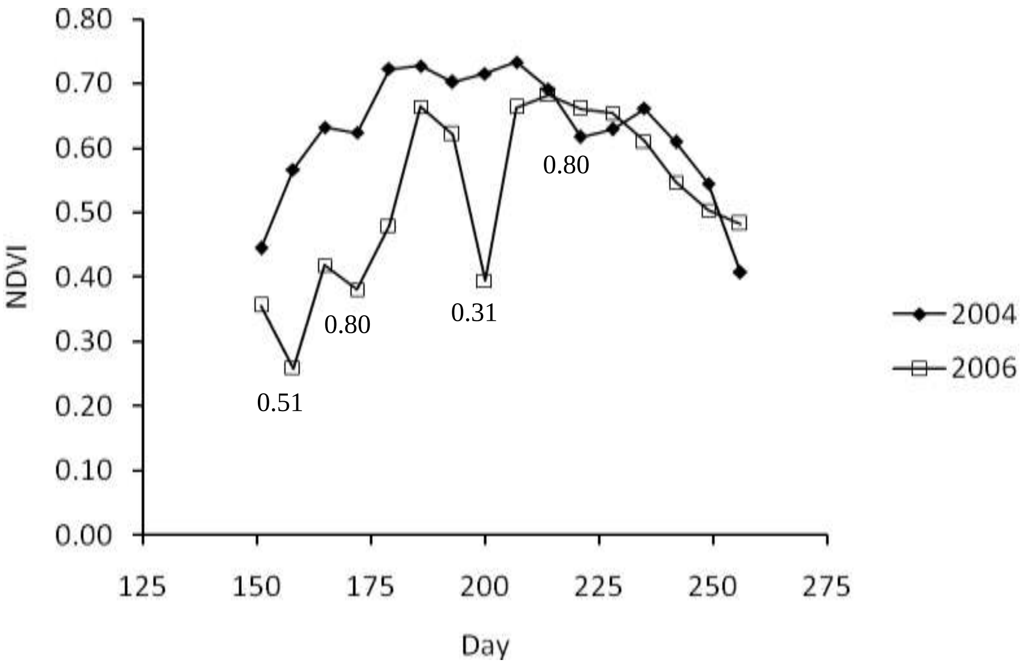

Fig. 3. Mean NDVI for the Noatak Basin subsection from MODIS weekly composites, in two example years. Means were computed using only pixels labeled as “good” (snow- and cloud-free). Dates with cloud contamination problems (proportion of “good” pixels 80% or less) are labeled with the proportion of “good” pixels. The unexpected dips in NDVI are related to cloudy periods and suggest cloud contamination of pixels labeled as “good”.

Weather Data

NDVI data were compared with weather data from the two nearby weather stations with long-term records reaching to the present (Western Regional Climate Center, 2010). These are station BETTLES FAA AIRPORT, 66° 55’ N, 151° 31’ W, 640 ft elevation, period of record 1951-2009; and station KOTZEBUE WSO AIRPORT, 66° 52’ N, 162° 38’ W, 10 ft elevation, period of record 1949-2009 (Fig. 2). Also useful here are the summer only records available from the interagency Remote Automated Weather Stations (RAWS). These are the Kelly RAWS (67° 56' N, 162° 18' W, 412 ft elevation, on the southern edge of the Delong Mountains section in western NOAT, 1990-2009, missing 1 year), the Kavet Creeks RAWS (67° 08' N, 159° 03' W, 235 ft elevation, in the Kobuk River Lowlands section, 1992-2009, missing 2 years), and the Noatak RAWS (68° 04' N, 158° 42' W, 985 ft elevation, in the Noatak Basin section, 1992-2009). Data for the Hoo Doo Hills RAWS in BELA were judged to be too intermittent to be useful here.

The effect of late winter snow depth, which undoubtedly affects green-up independently of spring temperatures, was not analyzed here. Snowfall and snow depth observations are made at Bettles and Kotzebue, but snowfall data have many missing records and snow depth is not summarized by year by WRCC. A USDA NRCS snow measurement site has recently been repaired in eastern NOAT and could be used for snow effects analysis in the future.

Results

AVHRR

Ecological sections differ in mean NDVI at the peak of the growing season (Table 3). The lowest mid-to late summer NDVI values (0.48) are found in the Arctic Brooks Range section, with extensive bare rock and alpine sparse vegetation. Intermediate values (0.57 to 0.59) are found in the Bering Straits Coastal Plain (where there are numerous small water bodies), the DeLong Mountains and Subarctic Brooks Range (with considerable bare rock and sparse alpine vegetation), and the Imuruk Plateau (with considerable area of sparsely vegetated lava flows). Higher values (over 0.60) occur in the tundra lowlands of the Chukchi Sea Coastal Plain and Noatak Basin, while the highest mean NDVI (0.68) is in the partly forested Kobuk River Lowland.

Mean NDVI is related to air temperatures. I tested the correlation of late June mean NDVI for each ecological section versus May-June average temperatures and also versus June average temperatures at the weather station (Bettles or Kotzebue) nearest the section. Correlations were stronger for May-June combined than June alone, though generally similar; F-test probabilities for regressions of NDVI versus May-June temperatures were $P < 0.05$ for all sections except the Noatak Lowland ($P = 0.065$) and the Arctic Brooks Range ($P = 0.64$; here Bettles is a poor choice for weather given its very different environment from the section, but no closer station has adequate records). The strongest correlations in our study area between May-June average temperature and late June NDVI are between the Kotzebue weather station and the two nearby coastal plain sections (Fig. 4).

Table 3. Mean late July NDVI values for selected ARCN ecological sections*.

Ecological Section	Mean NDVI	N (Years of record)
Arctic Brooks Range	0.48	15
Bering Straits Coastal Plain	0.59	14
Chukchi Sea Coastal Plain	0.63	19
DeLong Mountains	0.57	18
Imuruk Plateau	0.59	17
Kobuk River Lowland	0.68	18
Noatak Basin	0.63	19
Subarctic Brooks Range	0.57	15

*Based on AVHRR composite data, 1990-2009. Year of record vary because some years were rejected due to >20% cloud cover.

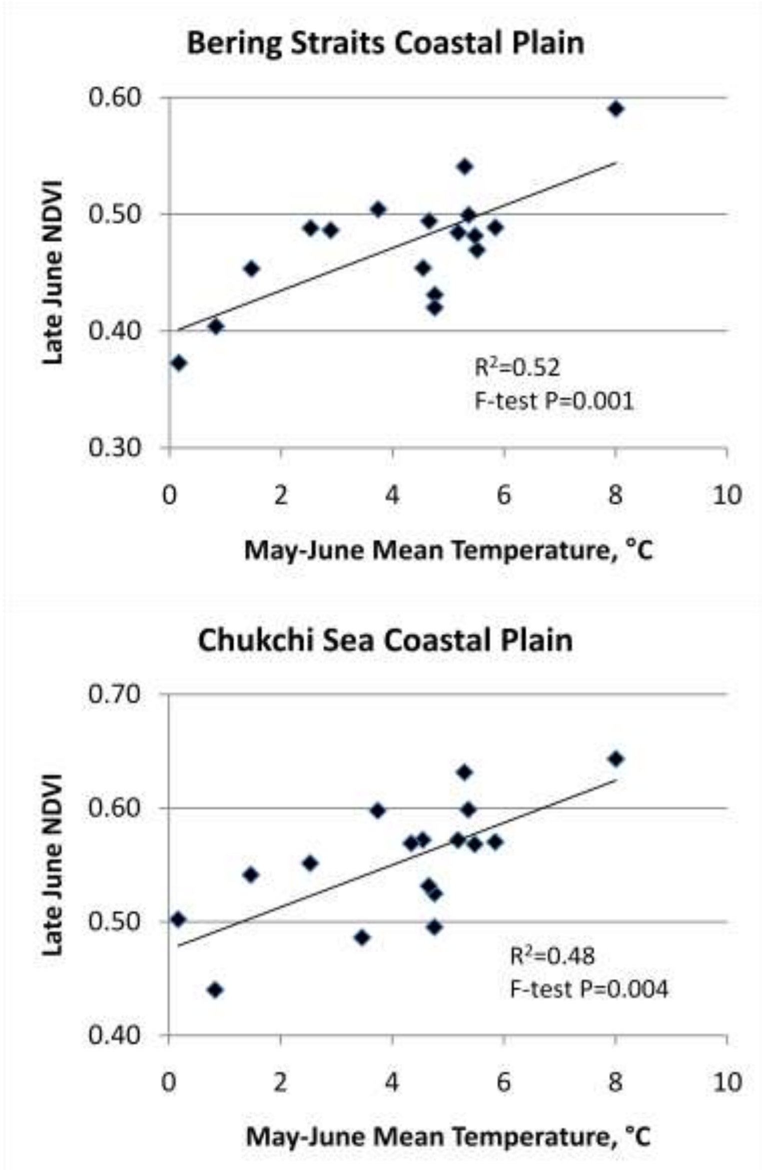

Fig. 4. Relationship between May-June mean temperature at Kotzebue and late June NDVI for two nearby ecological sections. NDVI is from AVHRR data for the period 1990-2009, including only years with less than 20% cloud cover.

Many of the ecological sections show a significant increase in AVHRR NDVI over the period 1990-2009 (Table 4). All regression slopes in Table 4 are positive, except for one clearly non-significant slope in late August. Highly significant regressions of NDVI versus year are concentrated in the more densely vegetated sections and the "greener" compositing periods, with the most in early August. Slopes of the significant regressions for late June are 0.004 to 0.006 NDVI units per year, amounting to an increase of approximately 0.1 NDVI units over the 20-year data period, or about 20%. Slopes for July and early August are nearly as great, 0.003 to 0.005 NDVI units per year, amounting to an increase of over 10% in 20 years (Table 4).

Table 4. Linear regressions of NDVI versus year for selected ecological sections*.

Section	Slope	R-squared	F-test Probability	N (years)	20-yr Change (%)
Early June					
Arctic Brooks Range	ND	ND	ND	2	ND
Bering Straits Coastal Plain	0.39	0.15	0.14	16	23
Chukchi Sea Coastal Plain	0.39	0.10	0.19	18	18
DeLong Mountains	0.27	0.06	0.44	13	14
Imuruk Plateau	0.46	0.19	0.08	17	24
Kobuk River Lowland	0.25	0.02	0.53	20	10
Noatak Basin	0.36	0.08	0.26	18	17
Subarctic Brooks Range	0.44	0.19	0.19	11	22
Late June					
Arctic Brooks Range	0.11	0.03	0.55	13	5
Bering Straits Coastal Plain	0.31	0.12	0.16	18	14
Chukchi Sea Coastal Plain	**0.41**	**0.23**	**0.04**	**19**	**16**
DeLong Mountains	0.45	0.21	0.06	17	20
Imuruk Plateau	**0.51**	**0.25**	**0.03**	**19**	**22**
Kobuk River Lowland	**0.61**	**0.32**	**0.01**	**19**	**21**
Noatak Basin	**0.58**	**0.25**	**0.03**	**19**	**23**
Subarctic Brooks Range	0.40	0.17	0.13	15	16
Early July					
Arctic Brooks Range	0.22	0.20	0.19	10	10
Bering Straits Coastal Plain	0.17	0.16	0.10	18	7
Chukchi Sea Coastal Plain	**0.35**	**0.28**	**0.02**	**20**	**12**
DeLong Mountains	0.29	0.20	0.09	15	11
Imuruk Plateau	**0.44**	**0.50**	**0.00**	**16**	**17**
Kobuk River Lowland	**0.46**	**0.43**	**0.00**	**19**	**15**
Noatak Basin	**0.47**	**0.34**	**0.01**	**19**	**17**
Subarctic Brooks Range	**0.33**	**0.25**	**0.05**	**16**	**13**
Late July					
Arctic Brooks Range	0.18	0.09	0.29	15	8
Bering Straits Coastal Plain	**0.41**	**0.47**	**0.01**	**14**	**15**
Chukchi Sea Coastal Plain	0.24	0.17	0.08	19	8
DeLong Mountains	0.06	0.01	0.71	18	2
Imuruk Plateau	**0.46**	**0.47**	**0.00**	**17**	**17**
Kobuk River Lowland	**0.35**	**0.31**	**0.02**	**18**	**11**
Noatak Basin	0.17	0.04	0.41	19	6
Subarctic Brooks Range	0.27	0.13	0.18	15	10

Table 4. (Continued)

Section	Slope	R-squared	F-test Probability	N (years)	20-yr Change (%)
Early August					
Arctic Brooks Range	0.14	0.08	0.36	13	6
Bering Straits Coastal Plain	**0.33**	**0.34**	**0.02**	**15**	**12**
Chukchi Sea Coastal Plain	**0.41**	**0.37**	**0.02**	**14**	**14**
DeLong Mountains	**0.27**	**0.31**	**0.03**	**16**	**10**
Imuruk Plateau	**0.34**	**0.40**	**0.01**	**15**	**12**
Kobuk River Lowland	**0.52**	**0.51**	**0.00**	**18**	**17**
Noatak Basin	**0.53**	**0.61**	**0.00**	**17**	**19**
Subarctic Brooks Range	0.26	0.15	0.12	17	10
Late August					
Arctic Brooks Range	0.23	0.16	0.33	8	13
Bering Straits Coastal Plain	-0.02	0.00	0.96	13	-1
Chukchi Sea Coastal Plain	**0.69**	**0.44**	**0.01**	**15**	**27**
DeLong Mountains	0.19	0.13	0.29	11	8
Imuruk Plateau	0.25	0.08	0.33	14	9
Kobuk River Lowland	0.23	0.08	0.29	17	8
Noatak Basin	**0.54**	**0.57**	**0.00**	**13**	**22**
Subarctic Brooks Range	0.31	0.23	0.14	11	13

*Based on AVHRR bi-weekly composite data, 1990-2009. Regressions with F-test probabilities of less than 0.05 are in **boldface**. Slopes are in units of NDVI*100/year. Early June data are missing for the Arctic Brooks Range due to snow and cloudiness. Percent change over 20 years is computed from the slope relative to 1990 y-intercept values.

Plots of average AVHRR NDVI for several sections versus year for the various parts of the growing season demonstrate a long-term increase amid considerable year-to-year variation (Fig. 5). For example, in the early 1990s in the Noatak Basin, an above-average early August had an NDVI value just over 0.6, but by the late in the 2000 decade, a year with 0.6 would be considered well below average. Some of the sections show cyclicality in NDVI. For example, the late June values in the Chukchi Seas Coastal Plain and early August values for the Noatak Basin appear to cycle with a period of 4 to 7 years (Fig. 5). The very low late June NDVI values for 1992 are probably the result of the 1991 eruption of Mount Pinatubo, which caused a global drop in temperatures in 1992 (Dutton and Christy, 1992). The amount of year-to-year variability shows no obvious trends with time (Fig. 5).

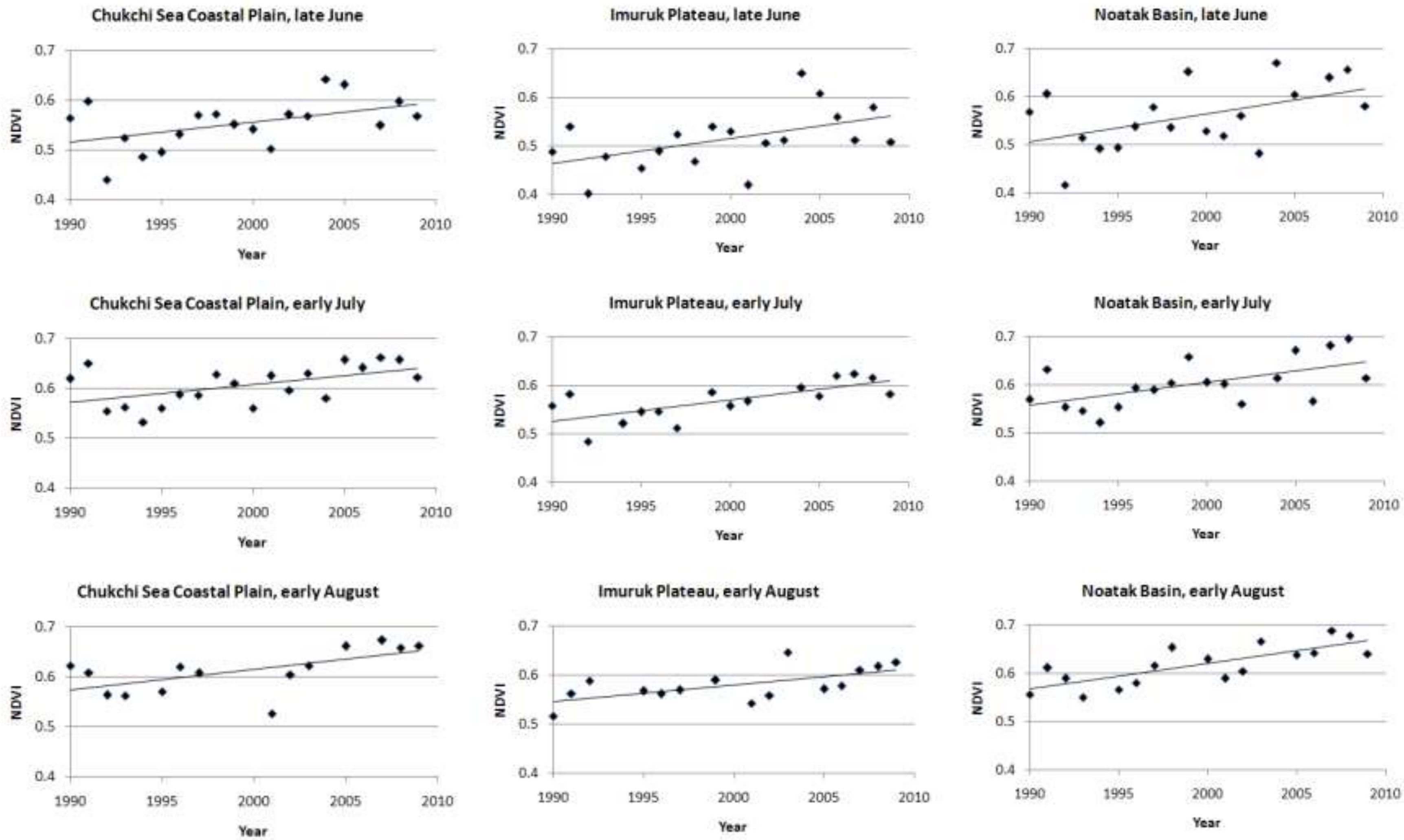

Fig. 5. Long-term trend in mean NDVI for selected seasons over the period 1990-2009 in three ecological sections (AVHRR data). Regression statistics for the trend lines are in Table 4.

Surprisingly, the observed increase in mean NDVI over the past two decades occurred without a corresponding increase in summer mean temperatures at Bettles or Kotzebue. Regressions of mean monthly temperature for each month from May through August individually versus year, and for June-August as a whole versus year, for the period 1990-2009 at Bettles and Kotzebue produce no highly significant results. The strongest relationship (the 3-month summer average temperature at Bettles, R-squared = 0.17 and F-test probability = 0.09) actually has a negative slope, i.e. summer temperatures may have decreased slightly during the period. No other regression has an R-squared above 0.1. Summer temperatures appear to be periodic, with the height of peak values higher after 1976 but not trending upward since that time (Fig. 6). This follows a statewide trend discovered by Hartmann and Wendler (2005), where temperatures have not increased significantly since an abrupt increase in 1976.

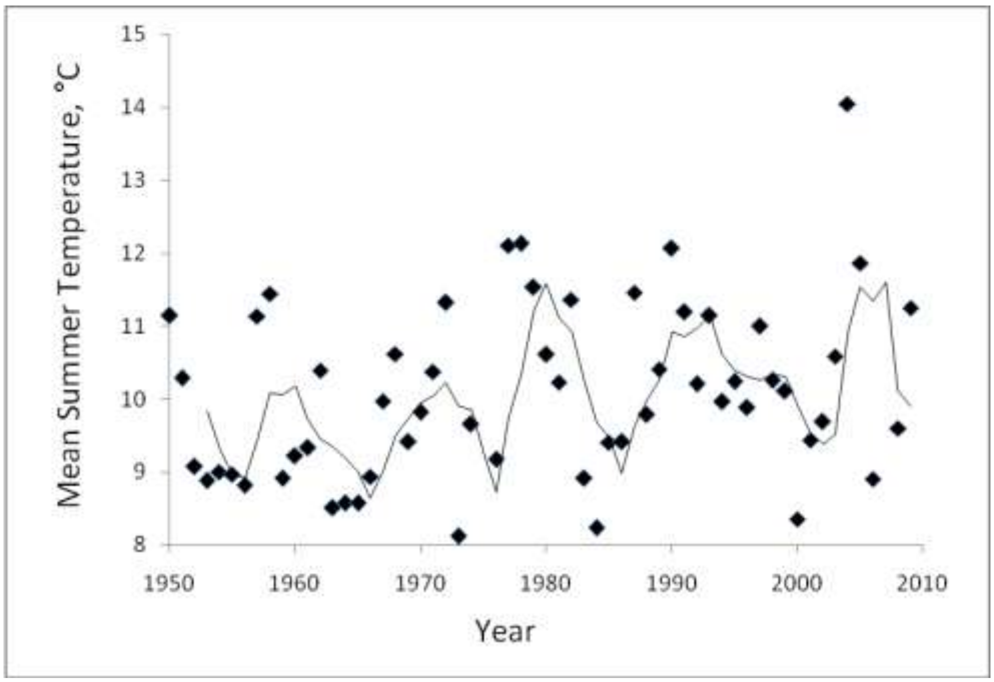

Figure 6. Long-term trend in mean summer temperature at Kotzebue, Alaska. The trendline is a moving 4-year average.

MODIS

The consistent compositing period of the MODIS data lend themselves well to analysis of trends within a growing season. Plots of the multi-year mean and standard deviation of mean NDVI within ecological sections versus day of the year (Fig. 7) display several interesting features: 1) the coefficients of variation (standard deviation/mean) in NDVI exceed 0.1 in the spring in most areas and in the mountainous sections reach 0.2, while late in the season they are mostly 0.05 to 0.1. This means that between-year variation can be 20% to 40% early in the season and 10% to 20% later. (Note that since the coefficient of variation is based on standard deviation, it describes the range to be expected about two-thirds of the time, not the more extreme events.) Spring variability is greater in the more easterly sections. 2) As was noted previously based on AVHRR data, mid-season MODIS NDVI is lowest in the sparsely vegetated, high mountain section (Arctic Brooks Range, < 0.5), fairly high (nearly 0.7) in the densely vegetated lowlands of the Chukchi Sea Coastal Plain and Noatak Basin, and highest (over 0.7) in the Kobuk River

Lowland. 3) The spring green-up is later and more protracted in the western, more maritime sections. NDVI rises gradually up to the day 204-210 composite (late July-early August) for the most westerly, coastal Bering Straits Coastal Plain and nearly as late in the Chukchi Sea Coastal Plain and Imuruk Plateau. In contrast, in the more continental Noatak Basin NDVI rises quite steeply up to days 183-189 (early July) and rises only slightly thereafter. The forested Kobuk River Lowland shows an even steeper early rise, completing most of its annual increase by the day 169-175 composite (late June). 4) NDVI for the partly forested Kobuk River Lowland levels off in September (days 246-252 and later) at a value above 0.55, which is distinctly higher than any other section and is probably due to the greenness of evergreen spruce (*Picea*) tree canopies.

The highest NDVI values over the period for which MODIS is available (2000-2009) occurred in the middle of the decade. The greenest Junes (highest NDVI values) were in 2004 or 2007 in all sections, with 2005 usually in second place. The lowest June values were in 2006 in most sections (Table 5). At the peak of summer season, years 2004, 2005, and 2007 continued to be green in many sections, though 2003 was greener in several. The lowest NDVI values at peak summer season were in 2000-2002. The senescence period was greenest in 2004, 2005, and 2007, and least green in 2003, 2002, and 2009.

These high and low NDVI values coincide with warm and cold weather as shown by weather stations temperature records. The greenest years – 2004, 2005, and 2007 - coincide with exceptionally warm summer monthly means at Bettles and Kotzebue (Table 6). These three years also had the three warmest summers (June-August averages) for the period of record at the Kavet, Kelly, and Noatak RAWS. The least green spring (2006) matches a cold June in Bettles (Table 6) and the coldest June on record for the Kelly and Noatak RAWS (the Kavet Creek RAWS is missing June 2006 data). June 2006 temperatures at Kotzebue were not exceptional, but the very cold May temperatures there in 2000 and 2001 may have led to low NDVI values in the two nearby coastal plain sections. The least green summer peak year (2000) coincided with exceptionally chilly July-August weather at Bettles and Kotzebue (Table 6) and the lowest July-August temperatures for the period of record at the three RAWS also. The early senescence in 2003 does not coincide with an obvious cold temperature event; it occurred in a typical August, albeit after a cold July at Bettles, Kotzebue, and the three RAWS. The other early fall, 2009, occurred in a rather chilly August after a warm July at Bettles but unexceptional August at Kotzebue or the RAWS.

Linear regressions of MODIS greenness of eco-sections in individual seasons versus year for the period 2000-2009 yield no highly significant trends for any ecological section in any season. All r-squared values are less than 0.3 and F-test P values for the slopes are all greater than 0.1. An example trend through the decade of MODIS NDVI (summer on the Imuruk Plateau) displays the mid-decade peak in greenness that overpowers any linear trend (Fig. 8).

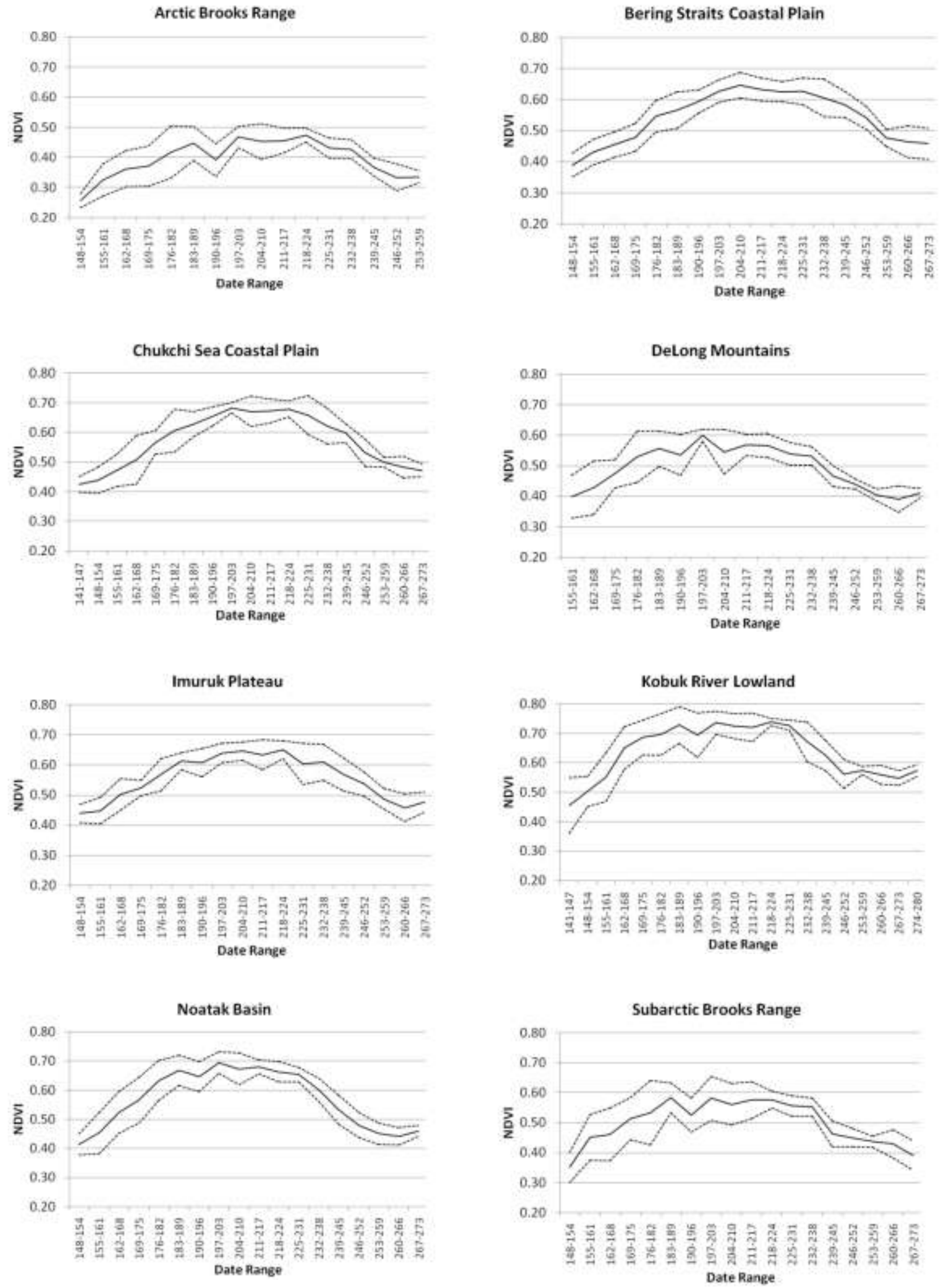

Fig. 7. Seasonal trend in mean MODIS NDVI for selected ecological sections. The solid line represents the mean of the section means for all years of record (2000-2009), and the dashed lines are the mean plus and minus one standard deviation in the section means.

Table 5. Years of highest and lowest NDVI values in the period 2000-2009 for selected ecological sections in the Arctic Network*.

Ecological Section	Year of highest NDVI	Year of 2nd highest	Year of 2nd lowest	Year of lowest NDVI
Green-up season				
Arctic Brooks Range	2004	2005	2008	2006
Bering Straits Coastal Plain	2004	2005	2008	2000
Chukchi Sea Coastal Plain	2004	2005	2006	2001
DeLong Mountains	2007	2005	2008	2006
Imuruk Plateau	2004	2005	2008	2006
Kobuk River Lowland	2007	2004	2000	2006
Noatak Basin	2004	2005	2001	2006
Subarctic Brooks Range	2004	2007	2009	2006
Peak greenness season				
Arctic Brooks Range	2003	2007	2009	2006
Bering Straits Coastal Plain	2008	2005	2002	2000
Chukchi Sea Coastal Plain	2004	2005	2002	2000
DeLong Mountains	2007	2003	2001	2000
Imuruk Plateau	2005	2004	2002	2000
Kobuk River Lowland	2005	2004	2001	2000
Noatak Basin	2004	2003	2001	2000
Subarctic Brooks Range	2003	2002	2009	2000
Senescence season				
Arctic Brooks Range	2004	2007	2000	2003
Bering Straits Coastal Plain	2007	2005	2003	2002
Chukchi Sea Coastal Plain	2007	2005	2009	2003
DeLong Mountains	2004	2007	2009	2003
Imuruk Plateau	2005	2004	2009	2003
Kobuk River Lowland	2004	2005	2002	2009
Noatak Basin	2004	2007	2002	2003
Subarctic Brooks Range	2004	2005	2009	2003

*Based on normalized NDVI values for weekly composites, computed from MODIS data. The green-up season is days 155-182 (June), peak greenness is days 197-224 (late July-early August), and the senescence season is days 225-252 (mid-August to early September)

Table 6. Percentile scores for monthly mean temperature at long-term climate stations near ARCN*.

Year	Kotzebue				Bettles			
	May	June	July	August	May	June	July	August
2000	*0.11*	0.51	*0.03*	*0.06*	*0.08*	0.78	*0.12*	*0.03*
2001	*0.00*	0.27	0.55	0.27	*0.06*	0.57	0.24	0.64
2002	**0.91**	0.60	0.38	0.33	0.46	*0.14*	0.32	*0.08*
2003	0.54	**0.98**	*0.15*	0.52	*0.15*	0.71	*0.03*	0.42
2004	**1.00**	**1.00**	**0.98**	**0.98**	0.74	**1.00**	**0.93**	**0.91**
2005	0.79	**0.82**	0.77	**0.89**	**0.96**	**0.91**	0.5	0.66
2006	0.45	0.34	0.33	*0.08*	0.67	*0.07*	0.25	0.31
2007	*0.16*	ND	**0.81**	**0.96**	0.79	ND	**1.00**	**0.92**
2008	0.61	0.36	0.47	0.45	0.44	0.51	*0.13*	*0.19*
2009	0.49	0.72	**1.00**	0.25	0.53	0.48	0.**81**	*0.14*

*For the entire period of record, 1949-2009 at Kotzebue and 1951-2009 at Bettles. Months with mean temperatures in the **upper 20th percentile** are in boldface and months with mean temperatures in the *lower 20th percentile* are underlined and italicized.

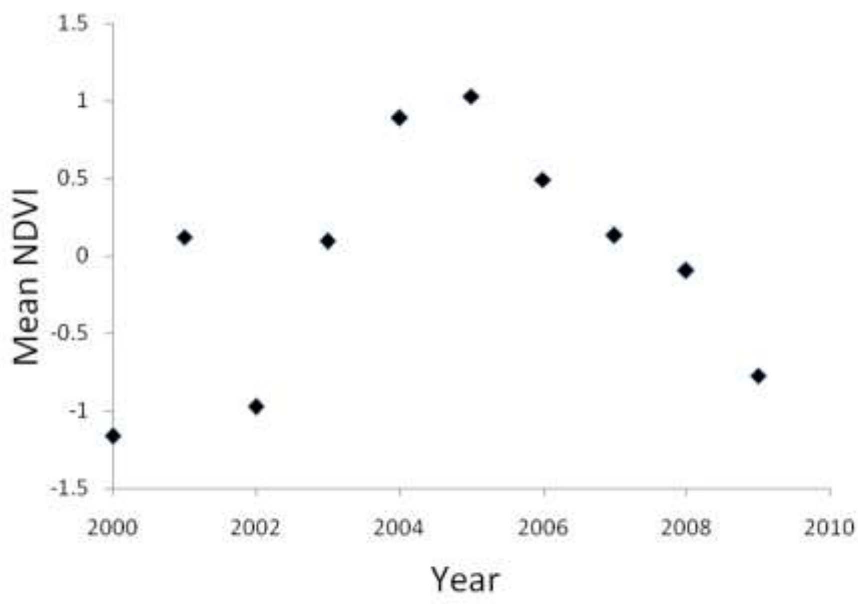

Figure 8. Mean MODIS NDVI for the Imuruk Plateau eco-section during the peak summer season (late July-early August) for the 2000-2009 decade.

Discussion

The good correspondence between mean NDVI (from both AVHRR and MODIS sources) for landscape units and monthly mean temperatures at area weather stations confirms that temperature is a dominant control of productivity in this cold-limited environment. My purpose here was not to exhaustively analyze the many climatic factors that might influence NDVI, but instead to verify the known relationship between NDVI and temperature in the arctic and thereby confirm that year-to-year variations in NDVI observed here have ecological meaning and are not artifacts of factors such as cloud contamination of the images or noise in the data. NDVI averaged over landscape units is a good regional integrator of the favorability of any particular growing season, and NDVI can be used as an explanatory variable in wildlife studies (e.g. Griffith et al, 2002). High and low NDVI events in ARCN coincided with high and low monthly mean temperature episodes in most cases, with the exception of early fall senescence events, which apparently are influenced by other factors (e.g., drought or brief extreme low temperatures).

Early summer NDVI values, averaged over an ecological section, vary significantly between years. The arctic is known for strong variations in spring weather that drive equally strong variations in growing season timing and productivity, with important effects on wildlife (Griffith et al., 2002). Some of the observed variability in NDVI could be due to cloud contamination, but I believe that the steps I took to avoid this problem (use of composites, screening of pixels flagged by the processing source as cloudy, and discarding all data for sections if cloudiness in the section exceeded 20%) were largely effective. The spring variability in NDVI is probably enhanced by the presence of residual snow in June in years with a late green-up, especially in mountainous areas. Between-year variability in NDVI is lower in mid- to late summer, though still significant.

The year-to-year variability or short-term cyclicality of NDVI occurs against a background of long-term increase of 10% to 20% over the 20-year period of 1990-2009 in the more heavily vegetated ARCN landscapes, according to AVHRR satellite data. A long-term increase in NDVI in an arctic region, limited by cold and dominated by long-lived perennials, could be explained by 1) an increase in the frequency or warmth of warm summers which result in greater leaf-area production, without major shifts in vegetation structure, or 2) a long-term increase in perennial biomass. The latter hypothesis is more likely to be responsible for the increase in NDVI during the period 1990-2009, given that there probably was no significant increase in summer warmth during this time. The long-term increase in NDVI is likely to be linked to the long-term increase in shrub biomass over recent decades that has been documented in arctic Alaska (Tape et al., 2006). Shrubby areas generally have higher NDVI than graminoid-dominated areas (Jia et al., 2004), as would be expected from their multi-tiered structure and large, bright-green leaves relative to graminoids. The Kobuk River Lowland ecological section, which is partly forested and also experienced an increase in NDVI, is dominated by open, subarctic forest with considerable open space available for an increase in tree or shrub density. Infilling of trees and shrubs leading to denser stands in recent decades has been document in the ARCN region (Rowland, 1996; Suarez et al., 1999; Tape et al., 2006).

This increase in biomass in the absence of an increase in summer temperatures is admittedly paradoxical. A discussion of this problem is found in Tape et al. (2006). For the purposes of the current study, I will simply note that an increase in warmth is probably responsible in some way for the biomass increase, though something other than warmth of summers in the last 20 years is apparently the critical factor. Examples of other possible warmth-related factors that could cause an increase in shrub biomass are increasing winter temperatures, or a prolonged response to warming that occurred more than 20 years ago.

The shorter term (2000-2009) MODIS data failed to replicate the multi-year increase in NDVI found by AVHRR, probably because a longer period of record is needed to see long-term trends amidst high variability and short-term (e.g. 4- to 7-year) cyclicality. The greenest years occurred mostly in the middle of the 2000 decade. The MODIS data are of high quality and I expect that as the length of the MODIS record increases it will begin to reveal long-term NDVI trends as well.

These results agree in general with a statewide study of summer maximum NDVI trends from 1982 to 2003 by Verbyla (2008). Verbyla also documented increasing greenness of northern Alaskan arctic lowlands and weak trends in high mountain areas. In western Alaska (i.e. BELA) and the Kobuk River Lowland, Verbyla found no trend where I found increasing NDVI. The increasing NDVI in the Kobuk River Lowland stands in contrast to decreasing NDVI over most of interior Alaska’s forests (Verbyla, 2008), perhaps owing to the location of the Kobuk River Lowland near latitudinal treeline.

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